

Rapid canopy closure for maize production in the northern US corn belt: Radiation-use efficiency and grain yield¹

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Abstract

Slow development of maize (*Zea mays* L.) canopies in northern areas of the USA may limit light interception and potential productivity. Whether radiation-use efficiency (RUE) and grain yield could be increased by earlier canopy closure was examined with two hybrids contrasting in canopy architecture and potential phytomass production. Early canopy closure was achieved using a combination of row spacings narrower and plant population densities (PPD) greater than typically used by local producers. Maximum interception of incident PAR (θ_{\max}) and total PAR intercepted from sowing to θ_{\max} (IPAR) increased with PPD. Thermal time to one-half θ_{\max} (TU_{0.5}) decreased with increasing PPD. Sowing in narrow (38 cm) rows did not affect θ_{\max} , IPAR, or TU_{0.5} in the tall hybrid, Pioneer 3790; nor did it affect grain yield, which increased with PPD up to 10 plants m⁻². Grain yield of the dwarf hybrid, SX123, was always less than that of Pioneer 3790, due to its low efficiency in converting intercepted PAR into phytomass. Both hybrids exhibited an optimum rate of canopy development in terms of θ_{\max} , IPAR, and TU_{0.5} for grain production. Optima for these parameters varied across years, but were similar for both hybrids and row spacings. These results indicate that hybrids adapted to the northern corn belt may yield more grain if sown at PPDs greater than commonly used to promote early canopy closure. Sowing to rows less than 76 cm wide will have less impact on grain yield. Productivity of hybrids prone to barrenness or with a low efficiency in converting PAR into phytomass, such as SX123, will not improve with earlier canopy closure.

1. Introduction

Average grain yield of maize (*Zea mays* L.) in the USA has increased steadily during the past six

decades and currently stands at about 7.5 Mg ha⁻¹ (USDA, 1995). Among other management factors, increased plant population density (PPD) and decreased row spacings have both contributed to the increase in grain yield per unit land area in the northern Midwest (Cardwell, 1982). Currently, most producers in this area sow maize in 76 cm rows at PPD between 5.0 and 7.5 plants m⁻². This combination of row spacing and PPD may not take full advantage of the relatively short growing season typical of the northern corn belt, however.

In the absence of biotic or abiotic stresses, maize

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yield is related to the amount of solar radiation intercepted by the crop (Tollenaar and Bruulsema, 1988; Muchow et al., 1990) particularly in a short growing season (Williams et al., 1965; Tollenaar and Bruulsema, 1988). Early canopy closure not only maximizes light interception (Williams et al., 1965; Gallo et al., 1985; Ottman and Welch, 1989), it also decreases evaporation from the soil surface (Karlen and Camp, 1985) and inhibits weed growth (Forcella et al., 1992). Timing of canopy closure can be altered by varying row-spacing and/or PPD (Williams et al., 1965; Tetio-Kagho and Gardner, 1988a; Ottman and Welch, 1989). At a given PPD, maize often produces 5 to 10% more yield when sown in rows less than 100 cm wide (Karlen and Camp, 1985; Nielsen, 1988; Hodges and Evans, 1990). But response to row spacing and PPD varies with available moisture and genotype (Karlen and Camp, 1985; Nielsen, 1988; Hodges and Evans, 1990). Only hybrids resistant to lodging and barrenness perform well when managed for early canopy closure (Buren et al., 1974; Nielsen, 1988).

Rapid canopy development may be especially critical in the relatively cool, short growing season typical of the northern corn belt. In Ontario, Canada, Tollenaar and Bruulsema (1988) observed an increase in grain yield and absorbed solar radiation with PPD up to 10 plant m^{-2} . Their measurements of light interception were limited, however, to periods after complete leaf area development. Major et al. (1991) also reported an increase in whole-plant dry matter with PPD up to 14.5 plants m^{-2} for 10 hybrids grown in Alberta, Canada. Neither study related early canopy development and light interception to grain yield.

This study was conducted to identify opportunities for improving maize productivity in the northern US corn belt. Relationships between grain yield and leaf area development, interception of photosynthetically active radiation (PAR), and radiation-use efficiency (RUE) were examined at PPD greater and at row spacing narrower than currently used in commercial production. Because canopy height can affect light interception (Boote and Loomis, 1991), a locally adapted tall hybrid (Pioneer 3790) and a dwarf hybrid developed specifically for narrow-row production (Cargill SX123) were compared under similar growing conditions.

2. Methods

2.1. Plant culture

Experiments were conducted at the University of Minnesota West Central Experiment Station, Morris, MN (45°35'N, 95°55'W) on a Hammerly clay loam soil (Aeric Calcaquolls, fine-loamy, frigid; USDA-Soil Conservation Service, 1972). Two commercial maize hybrids (Pioneer 3790, a dent type having 95 d maturity and a maximum height of about 3 m; and Cargill P.A.G. SX123, a flint type having a 75 d maturity developed for narrow-row production and having a maximum height of about 1.5 m) were seeded in east–west rows on 31 May 1986 and 4 June 1987 and thinned by hand to one of four PPD within the first 2 weeks after emergence. The range of PPDs exceeded those commonly used for both hybrids (Table 1). Pioneer 3790 was sown at 38 and 76 cm row spacings; SX123 was sown at 38 cm row spacing. Plots were 6.1 m by 15.2 m arranged in a randomized block design with four (1986) or five (1987) replications.

Prior to seeding, 100, 50, and 50 $kg\ ha^{-1}$ of N, P, and K, respectively, were broadcasted and incorporated into the soil using a rotovator. An additional 100 $kg\ ha^{-1}$ N was side-dressed 30 days after

Table 1
Target and harvest plant population densities (plants m^{-2}). Harvest data are means \pm SE for four or five plots

Hybrid	Row spacing (cm)	Plant populations		
		target	harvest	
			1986	1987
P3790	76	4.9	5.4 (0.4)	4.8 (0.6)
		7.4	7.2 (0.5)	7.4 (0.4)
		9.9	10.3 (0.5)	9.6 (0.6)
		12.4	12.2 (0.9)	11.4 (0.5)
P3790	38	4.9	5.6 (0.8)	5.2 (0.3)
		7.4	7.5 (1.8)	7.1 (0.2)
		9.9	10.6 (0.3)	9.4 (0.5)
		12.4	11.5 (0.3)	11.3 (0.5)
SX123	38	7.4	6.5 (0.8)	8.2 (0.5)
		12.4	11.7 (0.4)	12.6 (0.4)
		18.5	16.3 (0.6)	18.1 (1.2)
		24.7	24.8 (2.3)	25.9 (2.4)

sowing. Chemical weed control was achieved with a preemergence application of 2.2 kg ai ha⁻¹ alachlor and 3.3 kg ai ha⁻¹ cyanazine. Daily maximum and minimum temperatures, incident shortwave solar radiation, rainfall, and pan evaporation were measured at a weather station located 1.5 km from the experimental site.

2.2. Agronomic measurements

Aboveground portions of all plants in a 1 m² area of each plot were harvested every 7 to 10 days after emergence. Green leaf area was measured using a LI-COR 3000 (LI-COR, Lincoln, NE) area meter and expressed on a ground area basis. Dry phytomass was determined after drying at 70°C to constant weight. Grain yield and yield components were measured on the center two (76 cm plots) or four (38 cm plots) rows of each plot harvested after black layer formation. Grain yield is expressed on a 15.5% moisture basis. Harvest index (HI) was calculated from a 1 m² phytomass sample taken at the harvest. Grain weight and phytomass of the HI sample are expressed on a dry weight basis.

2.3. Light interception and radiation-use efficiency

Incident PAR (I_o) and the fraction of I_o intercepted by the canopy (θ) were determined between 1200 and 1400 h every 7 to 10 days on clear and partly cloudy days using a 1 m line quantum sensor (model LI-191SB, LI-COR, Lincoln, NE). I_o was measured at 1 m above the soil surface outside each plot area. PAR transmitted through the canopy (I_{tr}) was measured at the soil surface at an angle across two 76 cm rows or three 38 cm rows at four locations in each plot and averaged (Gallo and Daughtry, 1984). Intercepted PAR was calculated as $I_o - I_{tr}$ neglecting PAR reflected from the canopy and soil surface (about 40 $\mu\text{E m}^{-2} \text{ s}^{-1}$). The fraction of I_o intercepted was calculated as $\theta = (I_o - I_{tr})/I_o$.

The rate and extent of canopy development were quantified from the maximum fraction of light intercepted during the season (θ_{\max}) and thermal units (TU) required to achieve one-half θ_{\max} ($\text{TU}_{0.5}$). θ_{\max}

and $\text{TU}_{0.5}$ were calculated from logistic curves fitted to field data of θ versus accumulated TU, as described below. Accumulation of TU was assumed to be linear from 10°C to 30°C (Aspiazu and Shaw, 1972; Swan et al., 1987). This mathematical approach provided a comparison between treatments based on the entire pattern of canopy development.

Accumulated PAR intercepted by the canopy (IPAR) was calculated as $\text{IPAR} = \sum(\theta_d I_{od})$, where θ_d is the fraction of PAR intercepted each day, and I_{od} is the daily incident PAR. θ_d was calculated from logistic curves fitted to field data of midday θ versus days after sowing. Midday values for θ likely underestimate daily PAR interception (Flenet et al., 1996). Although the east–west row orientation minimizes time-of-day effects (Tetio-Kagho and Gardner, 1988a; Flenet et al., 1996), IPAR is a conservatively low estimate of accumulated intercepted PAR. I_{od} was assumed equal to 0.5 times the daily incident shortwave solar radiation (280–2800 nm) (Szeicz, 1974; Gallo et al., 1985) measured at the weather station with an Epply spectral radiometer (Epply Laboratory, Newport, RI). Daily IPAR were summed from sowing to θ_{\max} , which occurred 7 to 10 days after anthesis for all treatments. Because measurements of θ were discontinued before significant leaf senescence occurred, IPAR values represent PAR intercepted primarily by green leaf and stem material. Radiation-use efficiency (RUE) was calculated at θ_{\max} as total aboveground phytomass/IPAR and expressed as g DM MJ⁻¹ of intercepted PAR.

2.4. Statistical analysis

Field plots were arranged in replicated randomized blocks. Hybrids were main plots, row spacings were subplots, and populations were sub-subplots. LSDs between treatment means were calculated following a significant *F*-test. Where appropriate, data are presented as means \pm SE for individual treatments or sampling dates. Curves for θ versus TU were of the form $f(t) = B/(1 + (t/C)^D)$, where $f(t) = \theta$, $B = \theta_{\max}$, and $t = \text{TU}$. The same form was used to fit θ versus days after sowing. Curves were fitted to field data using the NLIN procedure (secant iterative method) in SAS (SAS Institute, 1989).

3. Results

Pioneer 3790 and SX123 were grown at a range of PPDs (Table 1) to alter the timing of canopy closure. In all cases, plant growth prior to canopy closure ($\theta = 0.95$) was vigorous and not limited by weeds, insects, or soil moisture. In both years, more than normal TU accumulated during leaf area expansion in May and June, and less than normal accumulated during grain filling in August and September (Table 2). Monthly precipitation was at or above normal levels throughout the growing season in 1986, but not in 1987. A soil water deficit developed during late July and early August in 1987 causing some leaf curling at the greatest PPDs.

The rate of leaf area development and maximum leaf area index (LAI) increased with PPD in both hybrids (Fig. 1). Row spacing did not alter the pattern of leaf area development, or the thermal time required for Pioneer 3790 to reach maximum LAI. LAI increased more rapidly in 1987 than in 1986 requiring approximately 100 fewer TU to reach a maximum at the same PPD. Pioneer 3790 achieved much greater LAIs than did SX123 at comparable PPDs. This difference reflected the greater area of individual leaves in Pioneer 3790 rather than more leaves per plant (data not shown).

θ increased with thermal time to a maximum 7 to 10 days after anthesis (Fig. 2). In general, canopies with greater LAI intercepted more incident light earlier in the season, regardless of row spacing or stature. θ increased more rapidly in 1987 than in 1986 corresponding to the more rapid increase in

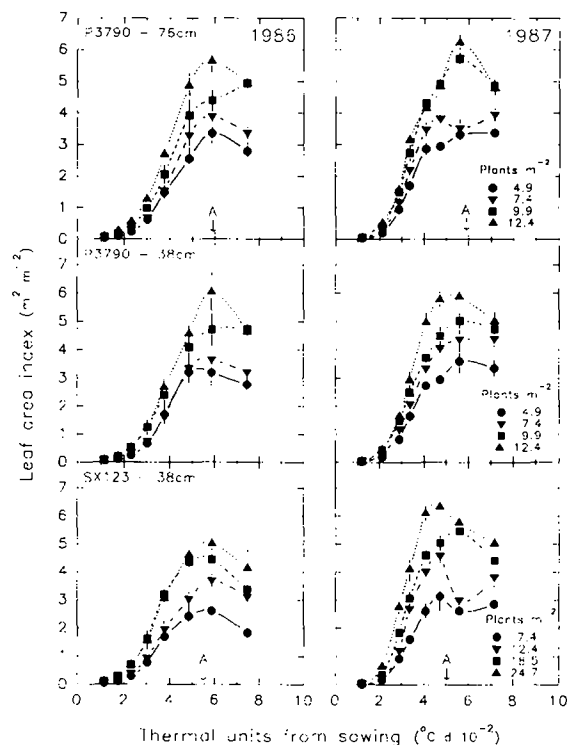


Fig. 1. Seasonal pattern of leaf area index (LAI) of Pioneer 3790 and SX123 grown at four population densities; Pioneer 3790 in 76 cm and 38 cm rows, SX123 in 38 cm rows. Data are means \pm SE. A = anthesis.

LAI. These results indicated that PPD had a direct effect on the timing and extent of canopy closure in these east–west rows, but row spacing did not, at least for plants of large stature. θ_{\max} , the maximum

Table 2

Monthly and seasonal rainfall, pan evaporation, and accumulated thermal units at Morris, MN in 1986 and 1987. Twenty-year averages are listed for comparison

	Rainfall (mm)			E_{pan} (mm)			Thermal units ($^{\circ}\text{C d}$)		
	1986	1987	20 y	1986	1987	20 y	1986	1987	20 y
May	98	74	76	193	208	202	134	194	108
June	107	48	101	213	205	219	354	300	266
July	164	46	89	209	190	225	364	378	360
August	140	37	76	169	178	191	238	268	321
September	82	73	56	92	123	140	106	149	149
Season	591	278	381	882	904	977	1138	1289	1204

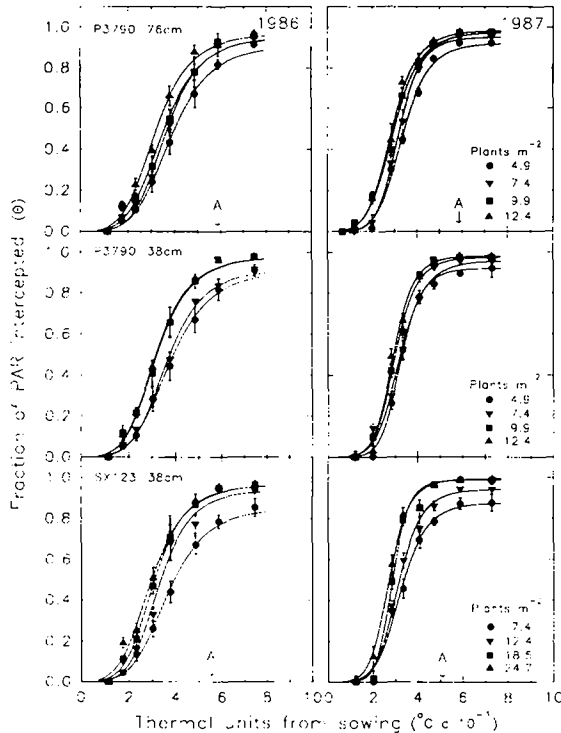


Fig. 2. Seasonal pattern of light interception in Pioneer 3790 and SX123 expressed as a fraction of intercepted PAR. Plants were grown at four population densities; Pioneer 3790 in 76 cm and 38 cm rows, SX123 in 38 cm rows. Field data are means \pm SE. Logistic curves fitted to field data are of the form $f(t) = B/(1 + (t/C)^D)$, where t = thermal units in $^{\circ}\text{C d}$. A = anthesis.

fraction of incident PAR intercepted, and $TU_{0.5}$, thermal time required to reach one-half θ_{\max} , were calculated to quantify this effect. θ_{\max} increased with PPD to a maximum of 0.98 (Table 3). Both SX123 and Pioneer 3790 canopies achieved this level of PAR interception, but θ_{\max} was smaller for SX123 than for Pioneer 3790 at comparable PPDs. At commercial densities, θ_{\max} reached about 0.95. For both hybrids, a maximum LAI in excess of 3.5 was required to achieve $\theta_{\max} > 0.95$, in agreement with earlier work (Williams et al., 1968; Christy et al., 1986; Tetio-Kagho and Gardner, 1988a). $TU_{0.5}$ decreased dramatically with increasing PPD. Row spacing did not affect θ_{\max} or $TU_{0.5}$ in Pioneer 3790. Both years produced similar results except that comparable treatments reached $TU_{0.5}$ much sooner after sowing in 1987.

The extinction coefficient k for PAR interception per unit leaf area ($k = -\ln(\theta)/\text{LAI}$) varied with PPD, but not with row spacing prior to canopy closure. For Pioneer 3790 in 76 cm rows, k decreased from -0.48 to -0.36 (averaged across years) with increasing PPD. In 38 cm rows at the same PPDs, k decreased from -0.48 to -0.39 . For the dwarf SX123, k also decreased with increasing PPD from -0.47 to -0.35 . These values agree with those of Flenet et al. (1996) who observed no difference in k for maize sown in 38 cm and 66 cm row spacings at $7.4 \text{ plants m}^{-2}$.

In general, sowing Pioneer 3790 in 38 cm row spacings did not increase RUE (Table 4). The only exception was at $7.4 \text{ plants m}^{-2}$ in 1987. Averaged across years and PPD, RUE for Pioneer 3790 was 2.7 g M^{-1} PAR intercepted, which was intermediate between values reported for maize grown in the southern USA (Kiniry et al., 1989) and Canada (Major et al., 1991). RUE of SX123 generally was less than that for Pioneer 3790 at comparable PPD. SX123 sown at $24.7 \text{ plants m}^{-2}$ was the least efficient of all treatments at converting intercepted PAR into phytomass.

The effects of PPD and row spacing on canopy closure were not reflected in grain yield. At both row spacings, yield of Pioneer 3790 increased with PPD up to about 10 plants m^{-2} (Fig. 3). Row spacing had no significant ($\alpha = 0.10$) effect on grain yield at any PPD tested. The decrease in yield at PPD greater than 10 plants m^{-2} in 1987 reflected the limited soil moisture late in the season (Table 2). Grain yield of SX123 peaked at approximately 12 plants m^{-2} , but was always less than that of Pioneer 3790. Harvest index of Pioneer 3790 did not vary with row spacing or PPD between 7 and 12 plants m^{-2} . Tetio-Kagho and Gardner (1988b) also observed that maize HI was fairly stable across of wide range of PPD. HI of the SX123 decreased rapidly at PPDs greater than $12.4 \text{ plants m}^{-2}$ due to an increasing number of barren plants (data not shown).

Kernels per ear and kernel size varied with PPD (Fig. 4). Kernel weight was more stable than was kernel number, but variation in both yield components contributed to the yield response to PPD. In the drier year of 1987, ears of Pioneer 3790 produced fewer, but larger kernels when sown in narrow rows. Response of ear number per plant to increasing PPD

Table 3

The maximum fraction of intercepted PAR (θ_{\max}) and thermal time from planting to one-half θ_{\max} ($TU_{0.5}$) for Pioneer 3790 and SX123 at different row spacings and plant population densities. θ_{\max} and $TU_{0.5}$ were calculated from logistic curves fitted to field data of PAR interception versus thermal units. I_0 : incident PAR; I_{tr} , PAR transmitted through the canopy

Hybrid	Row spacing (cm)	Target population (plants m ⁻²)	1986		1987	
			θ_{\max} ($I_0 - I_{tr}$)/ I_0	$TU_{0.5}$ (°C d)	θ_{\max} ($I_0 - I_{tr}$)/ I_0	$TU_{0.5}$ (°C d)
P3790	76	4.9	0.92	722	0.92	618
		7.4	0.95	662	0.95	578
		9.9	0.96	643	0.97	543
		12.4	0.97	582	0.97	519
P3790	38	4.9	0.91	713	0.92	599
		7.4	0.92	679	0.95	594
		9.9	0.98	583	0.97	540
		12.4	0.98	572	0.98	525
SX123	38	7.4	0.85	712	0.88	611
		12.4	0.94	612	0.94	574
		18.5	0.97	556	0.97	514
		24.7	0.97	542	0.98	486
LSD _{0.10}			0.04	75	0.03	23

was similar for both Pioneer and SX123; nearly every plant produced at an ear at PPD up to 12 plants m⁻². Thus, lower grain yields of SX123,

Table 4

Radiation-use efficiency (RUE) from sowing to θ_{\max} in Pioneer 3790 and SX123 at different row spacings and plant population densities. θ_{\max} , the maximum fraction of intercepted PAR, was achieved 7 to 10 days after anthesis

Hybrid	Row spacing (cm)	Target population (plants m ⁻²)	RUE(g MJ ⁻¹)	
			1986	1987
P3790	76	4.9	2.80	2.44
		7.4	2.65	2.50
		9.9	2.85	2.89
		12.4	2.73	2.17
P3790	38	4.9	2.89	2.24
		7.4	2.69	3.02
		9.9	2.76	2.89
		12.4	2.55	2.43
SX123	38	7.4	2.33	2.38
		12.4	2.19	2.09
		18.5	2.18	2.16
		24.7	1.85	2.12
LSD _{0.10}			0.47	0.49

compared to Pioneer 3790, resulted from its relatively small ears, which produced fewer and smaller kernels.

Plotting grain yield versus θ_{\max} , $TU_{0.5}$ and IPAR revealed an optimum rate and extent of canopy development for grain production (Fig. 5). Optima varied across years, but were similar within years for both hybrids and row spacings. In 1986, for example, maximum grain yield for both hybrids was achieved at $\theta_{\max} \approx 0.96$, $TU_{0.5} \approx 350$ TU from sowing, and IPAR ≈ 400 MJ m⁻². The optimum θ_{\max} was similar in 1987, but maximum grain yield was achieved at smaller $TU_{0.5}$ and IPAR values. Pioneer 3790 canopies were most efficient at converting IPAR into grain yield (g grain/MJ IPAR) at PPDs between 7.4 and 9.9 plants m⁻² (data not shown). Likewise, the most efficient SX123 canopies were those sown at 7.4 plants m⁻². Efficiency decreased markedly at greater PPDs, as observed by Andrade et al. (1993).

There was no apparent optimum θ_{\max} , $TU_{0.5}$, or IPAR for phytomass production (Fig. 5). Total phytomass of Pioneer 3790 increased with earlier canopy closure in 1986, but not in 1987. Early canopy

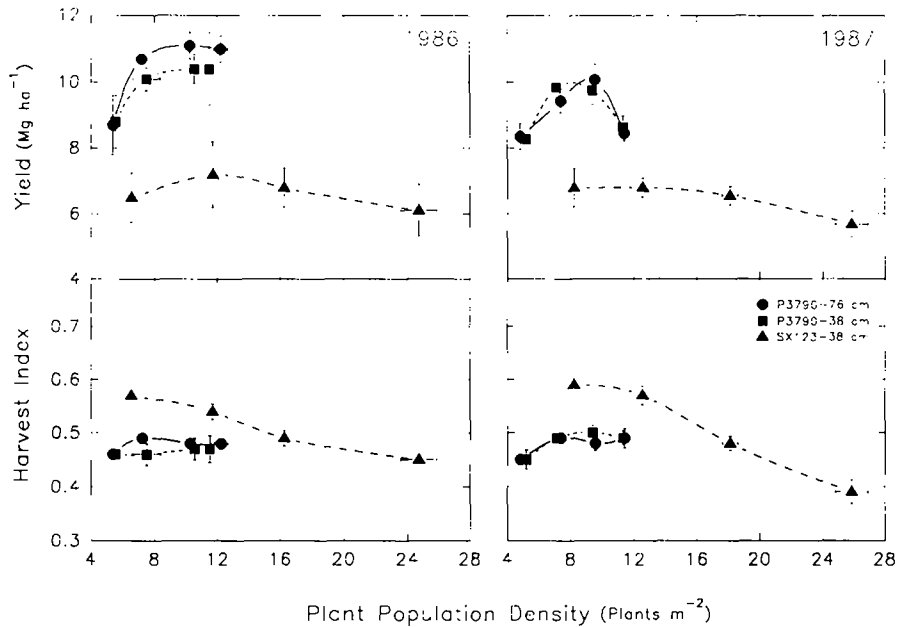


Fig. 3. Grain yield and harvest index (HI) of Pioneer 3790 and SX123 grown at four populations densities; Pioneer 3790 in 76 cm and 38 cm rows, SX123 in 38 cm rows. Data are means \pm SE. Yields are corrected to 15.5% moisture. HI is expressed on a dry weight basis.

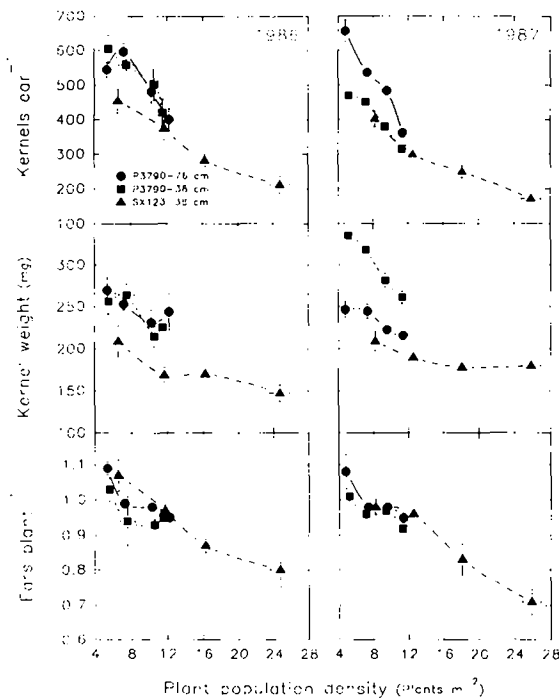


Fig. 4. Yield components of Pioneer 3790 and SX123 grown at four population densities; Pioneer 3790 76 cm and 38 cm rows, SX123 in 38 cm rows. Data are means \pm SE. Kernel weight is adjusted to 15.5% moisture content.

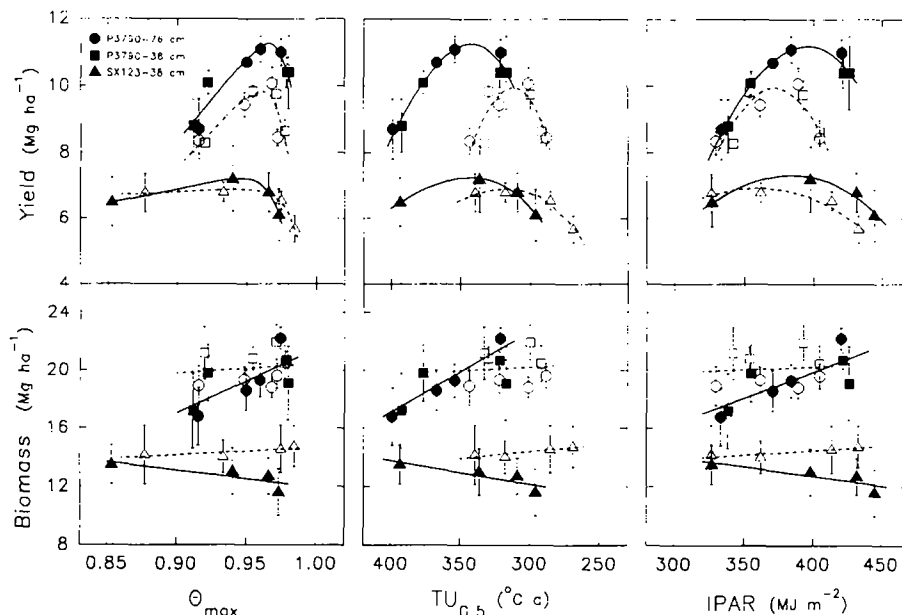


Fig. 5. Relationships between canopy closure and grain yield or total phytomass of Pioneer 3790 and SX123. Canopy closure was measured in terms of θ_{\max} , the maximum fraction of intercepted PAR; $TU_{0.5}$, thermal time to reach one-half θ_{\max} ; and IPAR; cumulative intercepted PAR from sowing to θ_{\max} . Hybrids were grown at four population densities; Pioneer 3790 in 76 cm and 38 cm rows, SX123 in 38 cm rows. Closed symbols = 1986, open symbols = 1987. Field data are means \pm SE. Fitted curves are provided to indicate general trends.

closure did not improve phytomass production in SX123.

4. Discussion

4.1. No grain yield advantage in 38 cm rows

Grain yield of Pioneer 3790 increased with PPD up to 10 plants m^{-2} (Fig. 3). Sowing this tall hybrid at 38 cm row spacing did not provide a yield advantage over the conventional 76 cm row spacing. Yield of the dwarf SX123 was much less than that of Pioneer 3790 at comparable PPD despite a relatively large HI. These results agree with Giesbrecht (1969) who found that row spacing did not affect grain yield of maize in the short growing season of Manitoba, Canada; although yield increased with PPD up to 7.5 plants m^{-2} . Taller, later-maturing hybrids were better adapted for greater PPD than were early-maturing, shorter hybrids (Giesbrecht, 1969). The lack of genotype by row spacing interaction or row spacing

by PPD interaction for grain yield in this and other studies (Nielsen, 1988; Ottman and Welch, 1989) indicates that maize hybrids that yield well at high PPDs will also do so as row spacings decrease.

Buren et al. (1974) concluded that barrenness was the major barrier to improving tolerance of maize to increased PPD. Evidently this problem has been minimized in Pioneer 3790 as the percentage of barren plants was small even at a PPD of 12.4 plants m^{-2} (Fig. 4). SX123 also maintained ear development at this PPD, but a large number of dwarf plants were barren at the greater PPDs typical of commercial production. Both hybrids produced fewer kernels per ear as plant population density increased. There was no evidence of tip-kernel abortion in Pioneer 3790, but unpollinated apical florets contributed to the yield loss at 12.4 plants m^{-2} in 1987. Pioneer 3790 grown in 38 cm rows produced smaller ear with fewer kernels in 1987 than in 1986; while kernel numbers per ear were similar both years in 76 cm rows. The reasons for the variation in kernel

numbers per ear and kernel weight with row spacing in 1987 are not known.

4.2. Radiation-use efficiency in narrow rows

As expected, sowing at greater PPD increased LAI and θ early in the season for both Pioneer 3790 and SX123 (Figs. 1 and 2). The increase in IPAR at greater PPD, however, did not necessarily result in an increase in crop phytomass (Fig. 5). Aboveground phytomass of Pioneer 3790 at anthesis was always greater than that of SX123, regardless of row spacing or PPD. Yet, SX123 intercepted as much incident PAR as did Pioneer 3790. The lesser phytomass production of SX123 determined its inferior RUE relative to Pioneer 3790 (Table 4).

Several authors have noted that dry matter production in maize is related more closely to the utilization of solar radiation than to its interception (Daughtry et al., 1983; Christy et al., 1986; Tollenaar and Bruulsema, 1988). Dry matter accumulation in maize increases linearly with PAR interception up to a maximum LAI of about $3.5 \text{ m}^2 \text{ m}^{-2}$ (Williams et al., 1968; Christy and Williamson, 1985). Growth rates continue to increase asymptotically with greater LAI to a maximum at $\theta_{\max} \cong 0.99$ (Williams et al., 1968). Canopy photosynthetic rates also increase linearly with LAI up to about $3.5 \text{ m}^2 \text{ m}^{-2}$ and asymptotically thereafter with greater LAI (Christy and Williamson, 1985). If PAR interception alone were limiting dry matter accumulation in the present study, then SX123 should have achieved phytomass similar to Pioneer 3790 at PPDs with comparable LAI (Fig. 2). Obviously, this did not occur even though the efficiency of PAR interception per unit LAI was greater for the dwarf hybrid SX123. For example, at $7.4 \text{ plants m}^{-2}$, k was -0.47 for SX123 versus -0.45 for Pioneer 3790; at $12.4 \text{ plants m}^{-2}$, k was -0.48 for SX123 versus -0.37 for Pioneer 3790. These results support the conclusion of Major et al. (1991) that relationships between LAI, θ , and dry matter accumulation are genotype specific. Tollenaar and Bruulsema (1988) reported that the efficiency of conversion of absorbed PAR into dry matter varied with hybrid and stage of crop development. And Christy et al. (1986) found that grain yield of maize was more closely related to photosyn-

thetic conversion efficiency (g grain/seasonal photosynthetic input) than to seasonal photosynthesis per se. Taken together, these results indicate that sowing maize in narrow rows and/or at greater PPD to increase light interception and photosynthetic production (Boote and Loomis, 1991) may not be sufficient to compensate for an inherently low RUE, as was evident for SX123.

Altering the pattern of plant spacing by narrowing the distance between rows had no practical impact on canopy PAR interception or dry matter accumulation of Pioneer 3790 (Figs. 2 and 5). Flenet et al. (1996) concluded that decreasing row spacing from 100 cm to 35 cm increased the efficiency of light interception in maize by providing a more even distribution of plants and foliage within the canopy. There was no significant difference, however, in interception efficiency between the 66 cm and 35 cm row spacings in their study. Ottman and Welch (1989) also reported no difference in θ_{\max} , phytomass or grain yield of maize planted in 38 versus 76 cm rows at 8 to 10 plants m^{-2} . The lack of a row spacing effect on θ probably reflects the rigid pattern of opposite and alternate leaf display in maize. There was no evidence in this study that leaf display was affected by row spacing or PPD. Decreasing the distance between rows at the same PPD may have caused greater PAR interception between rows, but evidently it allowed more PAR to be transmitted between plants within rows. Hybrids with a greater capacity for altering leaf display angles or with a whorled leaf display might be better suited for efficient light interception in narrow rows.

There was an optimum pattern of canopy development for both the dwarf and tall hybrids in terms of canopy closure and grain yield. Optima for θ_{\max} , $\text{TU}_{0.5}$ and IPAR varied across years, but were similar for both hybrids and row spacings. These results indicate that hybrids adapted to the northern corn belt such as Pioneer 3790 may yield more grain if sown at PPDs greater than $7.5 \text{ plants m}^{-2}$ to shorten the time between sowing and maximum light interception. Sowing at row spacings less than 76 cm wide will have less impact on grain yield, but may still provide a benefit for water-use efficiency (Karlen and Camp, 1985) and weed control (Forcella et al., 1992). Productivity of hybrids prone to barrenness or with a low efficiency for converting PAR into phy-

tomass such as SX123 probably will not improve with earlier canopy closure.

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